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Geophysical prospecting and remote sensing for the study of the San Rossore area in Pisa (Tuscany, Italy)

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A B S T R A C T

With the dual purpose of extending knowledge about the archaeological site of San Rossore and of assisting archaeologists in the recovery process of the ships, geophysical surveys integrated with remote sensing analyses were performed. The surveys were conducted at selected locations, placed on the plan of excavation (approximately 5 m above the ancient surface) and near the archaeological excavation area. Passive (Self Potentials) and active (Induced Polarization) electrical methods were used. The choice of geophysical methods was due to the peculiarity of the geological characteristics of the site. In fact, the sediments embodying the archaeological remains are mainly silts and silty sands, which are moderately conductive. Furthermore, a shallow groundwater hosted in the alluvial deposits (at approximately 2 m below the surface plane) is present in the site.

Induced Polarization results inside the excavation area allowed identifying some anomalies related to the ship boundaries, as well as other anomalies probably attributable to archaeological features. Additionally, the Self Potentials measurements carried out in the area near the archaeological excavation evidenced the presence of other archaeological features such as two ships, a pier and other structures. Furthermore, the multitemporal remote sensing data allow the identification of many traces related to filling of channels and ditches. Finally, the integration of the data contributed to a better interpretation of the archaeological site.

1. Introduction

Integrated geophysical surveys and multitemporal remote sensing analyses were carried out at the archaeological site of San Rossore, a very important river harbor of the Etruscan and Roman times, with the remains of many wooden ships, discovered near Pisa (Italy) (Fig. 1). The goal of these measurements was twofold: extending the archaeological knowledge of the site and helping the archaeologists with the recovery of the ancient ship. The geological site conditions, which point the presence of silts and silty sands that embodying the archaeological remains (moderately conductive) and a shallow groundwater hosted in the alluvial deposits at about 2 m below the surface plane, led the choice of geophysical methods. In particular, in order to obtain information about archaeological remains placed at depths exceeding 4 m and to delimit the ship (thus facilitating its recovery without damage), passive (Self Potentials) and active (Induced Polarization) electrical methods were used. Moreover, the analysis of multitemporal (1943–2013) remote sensing data, both aerial and satellite, allowed contextualizing the results of the geophysical surveys and contributed to the reconstruction of the ancient topography and palaeo-hydrographic pattern of the surrounding area, in the north-western periphery of Pisa.

The goal of the integrated geophysical prospecting and of the remote sensing analyses, according to a consolidated methodology (Scollar et al., 1990), was to obtain quantitative information on three aspects: i) the geometric and physical characteristics of the remains of the buried ship; ii) the extension of the harbor; and iii) the ancient organization of the surrounding territory. With regards to the first aspect, the results of the present work led to the development of geo-physical archaeological models of target objects that can be three-dimensional models of archaeological remains (buried ship). It can be used to help the excavation in a well defined area in order to facilitate recovery (also avoid damaging the buried remains) and to develop future strategies for archaeological excavations in the site. With regard to the second and third aspects, the results of the integrated multitemporal remote analyses and of the SP surveys provided a more balanced picture to map new buried archaeological features and allowed a more detailed characterization of the site.

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Fig. 1. The study area at the north-western periphery of Pisa (GeoEye-1 image of 2012 from Google Earth): A, San Rossore archaeological site; B, "ex Scheibler" area.

2. Study area

The study area is located in the north-western periphery of Pisa, about 200 m west of the medieval city walls, and concerns the most important archaeological site of San Rossore and the so-called "ex Scheibler" area, sited immediately to the west (Fig. 1).

Pisa developed on an alluvial plain built up by Arno and *Auser* (the ancient Serchio) rivers, which changed their hydrographic network over time due to natural and anthropogenic factors (Benvenuti et al., 2000; Sarti et al., 2010; Anichini et al., 2013: 13–27; Amorosi et al., 2013; Gattiglia, 2013: 11–79). Strabo (V, 2, 5) stated that Pisa was located at the confluence of the Arno and *Auser* rivers; their confluence was hypothetically located just west the urban area (a few dozen meters to the east of the study area: see below). In the Etruscan and Roman times, the modern Serchio River was split into three branches named *Tubra, Auserculus* and *Auser* (Fig. 2) near the gorge of Ripafratta. Probably, the first branch flowed to the north of Pisa, whereas the course of the *Auserculus* was similar to that of the modern Serchio. The *Auser* was the southernmost and main branch of the river, and flowed from north to south along the foothills of the Pisani Mountains and into the Arno River in Pisa. According to Strabo, also the Arno River originally consisted of three branches: the northernmost corresponds to the modern course (although, in the past, it was more sinuous), whereas scarce information is available about the two southern branches.

In the archaeological site near the railway station "Pisa – San Rossore" (approximately 3500 sqm large) about 30 ships have been unearthed, in more than one decade of excavation and restoration works (Bruni, 2000, 2003; 2006; Camilli and Setari, 2005; Camilli, 2004; Camilli et al., 2006a; Camilli et al., 2006b; see also http://www.cantierenavipisa.it). The materials originate from different loads of boats and are related to a period ranging from 3rd century BC to 7th century AD. The site was an Etruscan and Roman riverine harbor along the *Auser* and close to the city. From the geologic point of view, the site is a full water depression pertinent to a navigable watercourse: the overflow of Arno (which flowed less than a kilometer to the south) caused the formation of alluvial deposits, which have progressively moved towards north to the southern side (Benvenuti et al., 2002; Begliomini et al., 2003). Several alluvial events have characterized the site, from the 2nd century BC to the late ancient age: i) a first alluvium in the Hellenistic Age (first decades of the 2nd century BC); ii) a second one in the Augustan-Tiberian Age; iii) a third one at the end of the 2nd century AD; iv) another one between the 3rd and 5th century AD; v) a fifth one after the 5th century AD; and vi) the last alluvium dating between the end of the 6th and the beginning of the 7th century AD. As a result, the site records some strong floods that destroyed the ships, buried in the alluvial deposits. The stratigraphy and sedimentology of these deposits suggest that the flood events were controlled by centennial climatic and eustatic cycles (Benvenuti et al., 2006).

During the life of the river harbor of San Rossore the coastal morphology was different from today (Figs. 2–3). Into the Pisa-Arno delta area, the coastline during Roman Age was located approximately 6 km east of its current position. Strabo (V, 2, 5) during the 1st century AD positioned Pisa about 20 *stadi* from the coastline (approximately 3.8 km). A large bay existed to the south-west of Pisa and was known as *Sinus Pisanus*; it gradually developed into a wetland, now entirely silted over. In the Roman Age, as also reported by Rutilio Namaziano (*De reditu suo*, 1, 527–540; 2, 11–12),

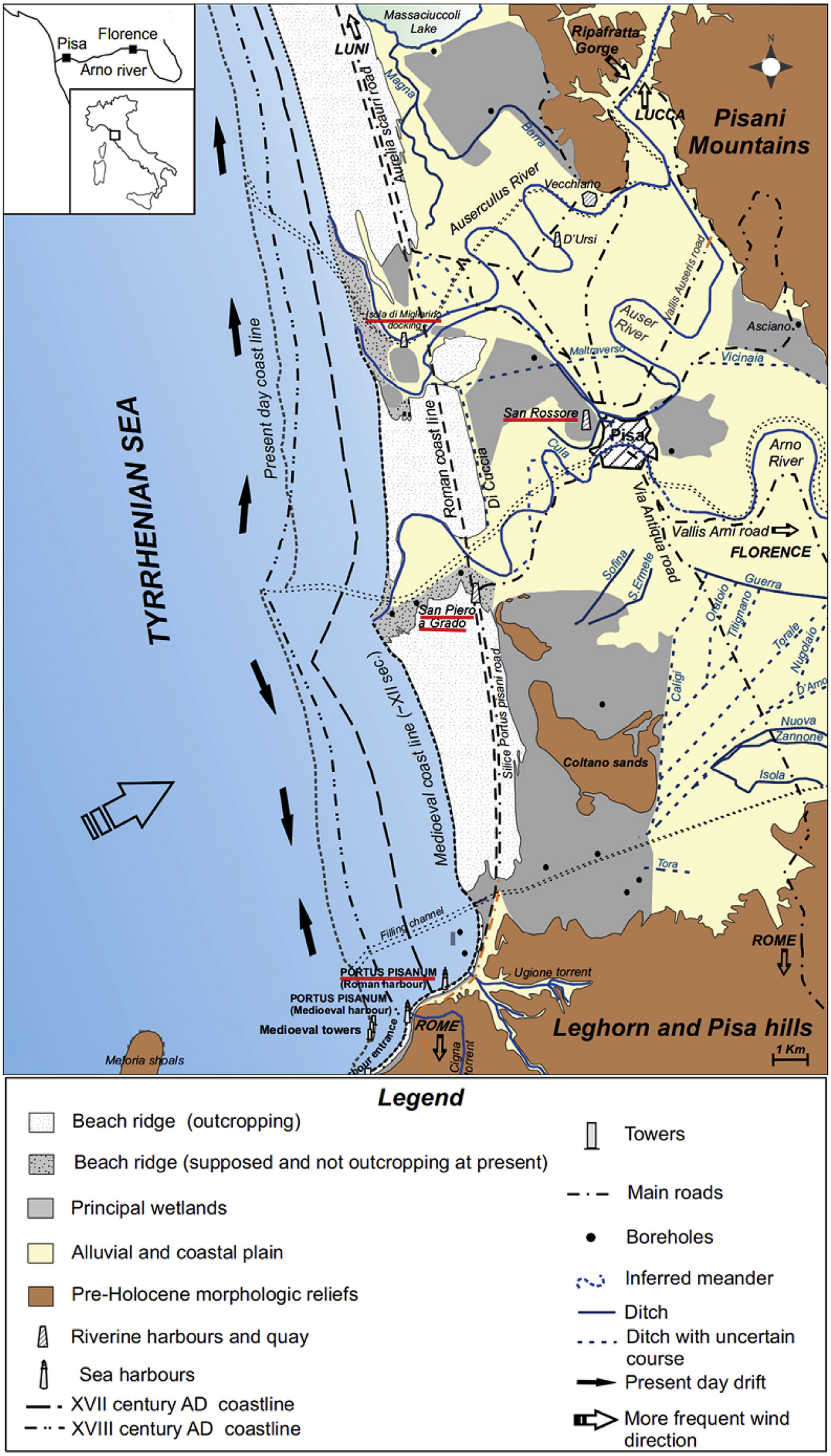

Fig. 2. Paleohydrography of the Pisa plain (from Sarti et al., 2010, Fig. 4A; with few additions).

Fig. 3. The Pisa plain in a GeoEye-1 image of 2013 (from Google Earth): the main Roman harbors and the coastline of the same period are indicated.

Pisa possessed two harbors, which were nine miles apart from each other: the *Pisae fluvius* was near S. Piero a Grado at the Arno River mouth, and the *Portus Pisanus* was located at the southern edge of the bay, i.e. the *Sinus Pisanus*, in the area of the northern periphery of modern Livorno (Pasquinucci and Mazzanti, 1987; Pasquinucci, 2003b; Camilli, 2004: 54–59; Ducci et al., 2005; Pasquinucci and Menchelli, 2010). Another important Roman river harbor, the *Auserculus,* was present up north, near Migliarino Island, at the mouth of one of the northern branches of the Serchio. The San Piero a Grado river harbor was less important than the *Portus Pisanus*, and in the Medieval Age it became progressively more distant from the river mouth due the coastal progradation. *Pisae* and *Portus Pisanus* were well connected by waterways and land, in particular from the *Via Aurelia*. In *Portus Pisanus*, the area of the basin in use in the late republican period was progressively filled up with deposits of *posidonia*; eventually, it was abandoned in the 1st century AD, with a gradual shift towards the south-west of the main harbor, which remained active during the Middle Ages. In this context, where the activities of the main harbor *Portus Pisanus* were supplemented by smaller harbors, the site of San Rossore (with many river boats found and dated between the 2nd century BC and 7th century AD) provides significant data on inland shipping.

Pisa became a *municipium* in 86 BC and *Colonia Iulia Opsequens* in the Augustan age. Following the colonial deduction, also the pattern centurial of Pisa must have been traced; a lot of traces remain still visible in aerial photos, also as persistence in the pattern of road layouts (Fraccaro, 1939; Castagnoli, 1958; Ciampoltrini, 1981, 43; Schmiedt, 1989; tav. XXXIII; Pasquinucci, 1994; Sangriso, 1999; see also Bini et al., 2012, Fig. 9.3). The centuriation of Pisa has been defined after an intense deforestation; as limits for the division into lots were used roads and channels, which, at the same time, constituted good lines of communication and served to drain the area. In the site of San Rossore the intersection between a centurial channel and the *Auser* river has been brought to light, while the investigation about pollen have confirmed the existence of uncultivated lots, such as respect areas by the river; therefore, these lands were framed in centuriation but left fallow.

3. Geophysical surveys

3.1. Strategies and methods

Geophysical surveys in the San Rossore area were performed in June 2000 inside the archaeological site, and in June 2002 in the external area to the west of the excavations; the research was a cooperative work between the University of Firenze and the University of Salento (Carrozzo et al., 2000, 2003; Nuzzo, 2005). The geological site conditions and the necessity to obtain information about archaeological remains placed at depths exceeding 4 m led to the choice of geophysical methods.

Geologically, the archaeological site of San Rossore lies in the area known as the Pisan lowlands, a sedimentary basin of alternating continental and marine origin, whose formation began in the late Miocene period (approximately 10 million years ago), following tectonic subsidence in a region previously characterized by the formation and rise of the Northern Apennines. The palaeoenvironment of the region was characterized by the presence of two rivers, the Arno and the now disappeared *Auser*, as well as minor watercourses and canals (see above § 2). As a result of the accumulated alluvial deposits of the Arno, the coast is now at considerable distance from Pisa and the characteristics of the surrounding countryside have been altered significantly by the gradual expansion of marshland. Data from archaeological excavation and geological observations (core samples) allowed the reconstruction of the stratigraphy of the uppermost 10 m of sediments in the San Rossore area. About 3 m of sand rest on relatively thick clay deposits, not yet reached by the excavation. These sands, in turn, lie under approximately 2 m of alternating sand and silt deposits in the northward sloping layers containing the shipwrecks and other archaeological deposits. This level progressively diminishes in depth and coarseness northwards, and its stratification is tentatively attributed to exceptional flooding of the Arno, which laid down lenticular sand deposit in the dry area between the river and its right bank. The remaining layers of sediment consist of silty-clayey muds from more routine flooding and from backfill dumped in historical times (Bruni, 2000). The excavation revealed that in ancient times the southernmost sector of the harbor basin was subjected to a series of phenomena leading to its progressive silting up: the various lenticular sediments are, indeed, inclined northwards in the direction of the coastline, which in Roman times laid approximately 3–4 km west of the excavation (Carrozzo et al., 2003). The nature of the sediments, observed so far, in the alternating sand and silt deposits suggest that the area was repeatedly flooded and sometimes so violently to move the ships and diverse portions of their cargo, although these events have not yet been dated (Carrozzo et al., 2003).

Active (Induced Polarization) and passive (Self Potentials) electrical methods were used. In particular, the first method was applied inside the archaeological site of San Rossore, while the second one was employed in an area to the west of the excavation area (Fig. 4).

The Induced Polarization (IP) extends the resistivity method by making an additional measurement of the ability of the ground to store electrical charge.

Originally developed for mineral exploration (Madden and Cantwell, 1967; Gateau et al., 1980), it is currently being employed also in the fields of environmental and engineering geophysics (Ogilvy and Kuzmina, 1972; Roy and Elliot, 1980; Ruhlow et al., 1999; Sauck et al., 1998). IP instruments measure both the conductive and capacitive properties of the subsurface using either time domain or frequency domain techniques. The low frequency capacitance of rocks and soils is primarily a function of the surface chemical properties of the sample. In non-metallic samples, the IP response is an indicator of surface area and charge density of the material. IP measurements are therefore sensitive to clay content as well as to mineralogy and pore fluid composition. IP methods have been used to estimate the hydraulic properties of rocks and soils as well as to map subsurface contamination (Seara and Granda, 1987; Slater et al., 2000; Sturrock et al., 1998) The method is also sensitive to subsurface metals (Reynolds, 2011). The IP method have also been used for archaeological survey (Aspinall and Lynam, 1968, 1970; Schleifer et al., 2002; De Domenico et al., 2006; Florsch et al., 2011; Schleifer et al., 2002; Weller et al., 2000; Florsch et al., 2012).

The IP can be measured either in the time or frequency domain using a standard earth resistance array with steel and non-polarizing current and potential electrodes, respectively. Time domain measurements are performed by applying a square wave signal to the current electrodes and recording the decay of any induced polarization voltage over a period of time shortly after the applied field has been removed. When the current is applied, the measured voltage will rapidly rise to within a few percentage points higher/lower than the maximum voltage, and then it approaches (but, theoretically, never reaches) this maximum asymptotically. Similarly, when the current is removed, the measured voltage will fall to the same induced polarization voltage just above zero before decaying over a time period of up to 1 s or more (Reynolds, 2011).

Fig. 4. Location of the surveyed areas using geophysical prospecting inside the San Rossore archaeological site (A: Induced Polarization method), and immediately to the west (B: Self Potentials survey) (BLOM-CGR aerial photo of 2012, from Bing).

The Self Potential (SP) survey is one of the oldest methods in geophysical exploration, and it is still used for solving many problems in applied geophysics. It is very rarely used in archaeological prospection because the related phenomena are not very well known. The application of SP to archeology aims to discuss the different SP phenomena responsible for anomalies on archaeological sites, such as electrokinetic, electrochemical and other SP effects (Wynn and Sherwood, 1984; Drahor et al., 1996; Cammarano et al., 1997; Drahor, 2004). Drahor (2004) provides a summary of the possible sources of self-potential anomalies with regard to archaeological features. The SP measures the natural or spontaneous potential difference that exists in the subsoil in the absence of any artificially applied current. They map buried structures and altered soil related to physical variations caused by temperature, pressure gradient, porosity, fluid migration, resistivity variation and moisture content of soil (Reynolds, 2011). SP measurements are widely used thanks to the relative simplicity and to the low cost of the required equipment. In fact, field measurements are made between two non-polarizing electrodes connected to a suitable high-impedance voltmeter. In this research, the SP data were collected in the total field measurement technique. For this acquisition technique, one measurement electrode is fixed at the base station, and the other electrode is moved along the survey line.

3.2. Geophysical prospecting inside the archaeological excavations area

The Induced Polarization measurements inside the archaeological site of San Rossore were carried out on a surface of 22 m × 22 m using a 48-channel, Syscal R1 Resistivity Meter from IRIS Instruments. It was employed in a multielectrode configuration using 48 electrodes. To improve the data quality, especially in depth, a "high-resolution" survey technique with overlapping data levels (Loke, 2001) was chosen. This technique allows increasing the number of data points. Data were collected using a dipole–dipole array, along 1 m spaced parallel profiles oriented approximately E–W (Fig. 5). Employing 48 electrodes at 1 m intervals, 7128 data points were collected.

The first step in the data processing consists in obtaining a pseudo-section by plotting the apparent IP versus the depth for each midpoint of a given electrode configuration. The inversion of the data is carried out according to an iterative process, which aims at minimizing the difference between the measured pseudo-section and the calculated pseudo-section based on a starting model. This model is updated after each iteration until it reaches an acceptable agreement between measured and calculated data or until no further improvements are possible. The ErtLab software, manufactured by Multi-Phase Technologies, LLC, was used to automatically invert the IP acquired data and to yield a 3D IP model. Its numerical core is based on tetrahedral FEM, and inversion was performed with a robust inversion (data variance iterative reweighting). The results of the inversion of the electrical data set, given as horizontal slices (parallel to the surface) through the ground, are shown in Fig. 6.

In particular, Fig. 6 shows the IP model at four different depths. It is possible to note a high IP (indicated as chargeability) area (about 150 ms) in the center part of the survey area in layers 2 (1.5 m depth), 3 (2 m depth) and 4 (2.5 m depth). The topmost layer (layer 1 in Fig. 6) exhibits a larger homogeneous area with low chargeability variations. As for layer 2, which lies at a depth of 1.5 m, it shows more gradual variations in the IP model values; here, two anomalies (labeled A and B) having chargeability values of about

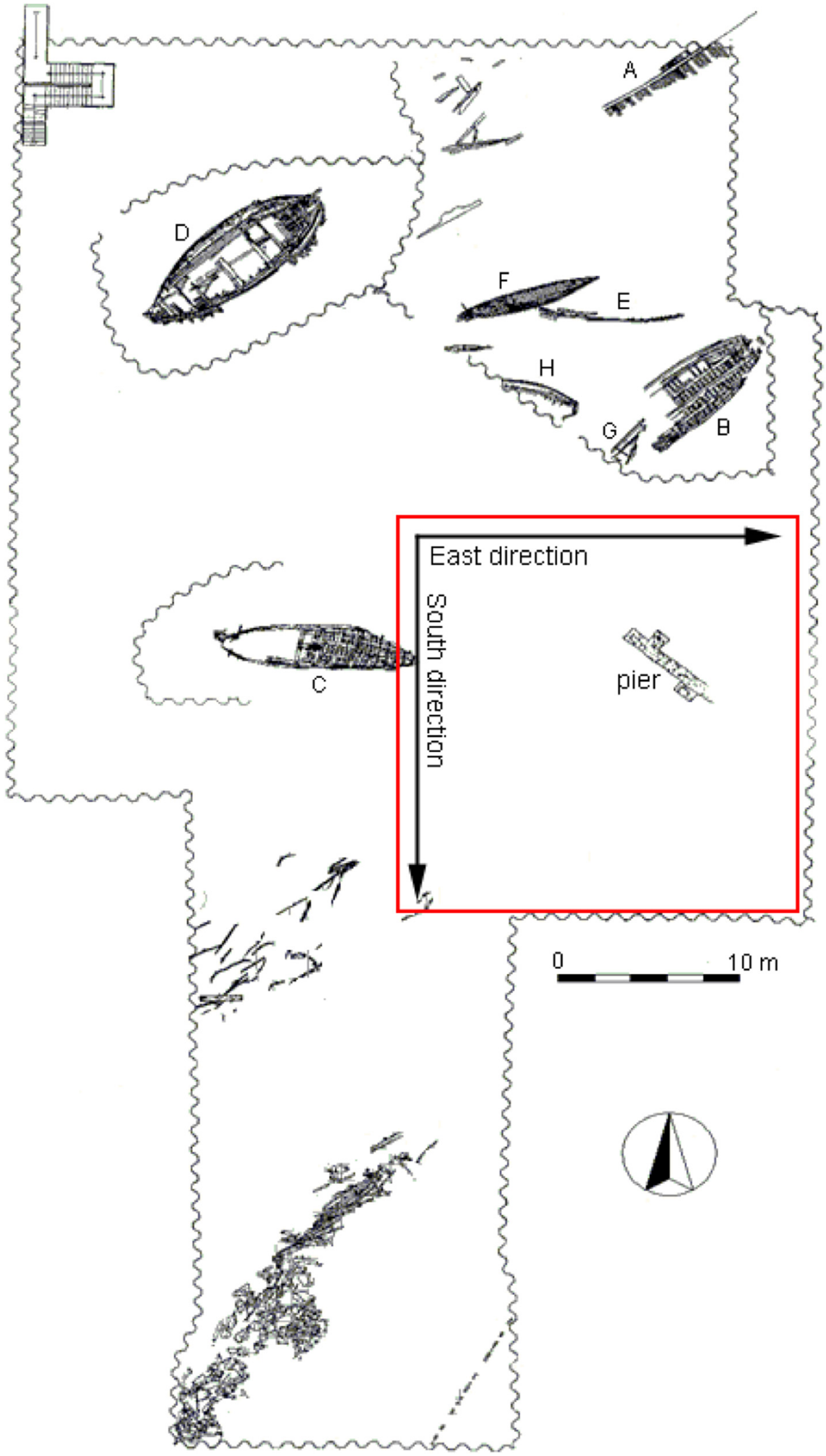

Fig. 5. The IP surveyed area (red square) inside the archaeological excavation site of San Rossore. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

80 ms are clearly visible. Because of the shape and alignment of the discovered pier (which is clearly visible in Fig. 5), these two anomalies could be interpreted as due to the pier ("A") and more likely to a ship ("B"), the same identified thanks to previous GPR measurements (Carrozzo et al., 2003, Figs. 7; B and 9, B). Anomaly labeled B is clearly visible also in the layers 3 and 4. Overlaying the excavation plan with the layers 2 and 4, the position of the ship near the pier becomes fairly clear (Fig. 7).

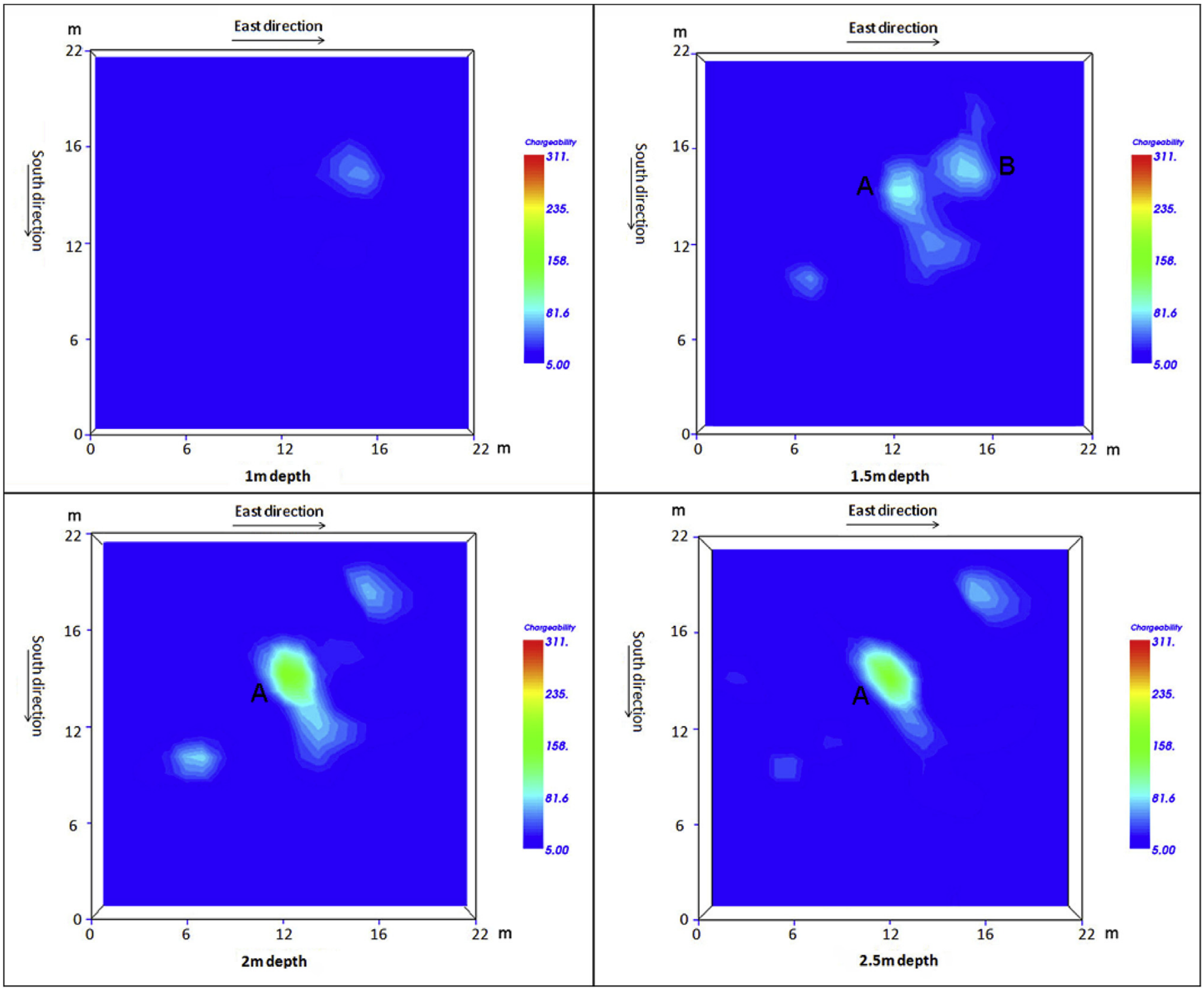

Fig. 6. Depth slices (between 1 and 2.5 m depths) of the San Rossore archaeological site: high IP (indicated as chargeability) anomalies indicate probable features of archaeological interest.

The 3D images of IP can easily be visualized by 3D contouring of iso-IP volumes (Fig. 8). In this representation, the transparency function is defined by two threshold values of the IP, IP1 and IP2 (IP1 < IP2). In the intervals IP < IP1 and IP > IP2, data are rendered as transparent; therefore, only the data in the interval IP1 < IP < IP2 are visualized. The threshold calibration is a very delicate task. In fact, by lowering the threshold value, not only the visibility of the main anomaly is raised, but also that of the smaller objects and noise increases. In Fig. 8, the IP data set is displayed with iso-IP volumes using a threshold value ranging from 80 to 150 ms. The continuous high IP anomaly are more visible. This kind of visualization allows the anomalies chargeability, already shown in Figs. 6 and 7, to be emphasized. The spatial position of the ship is clear.

3.3. Geophysical prospecting near the archaeological excavations area

The Self Potential signals were measured at the ground surface in a set of 864 measured points located along nine parallel line; the surveyed area (about 35 m × 45 m) is located immediately to the west of the excavation area (Fig. 9).

Each electrode (stainless and non polarizing) was placed inside a hole 10 cm deep and filled with a moistened bentonite and gypsum mixture (thus ensuring good contact between the electrode and the ground). Measurements of the self-potential signals were carried out with a Keithley 2701 multichannel voltmeter, using non-polarizing Pb/PbCl2 (Petiau) electrodes (Perrier et al., 1997). The voltmeter was connected to a laptop computer where the data were recorded. All the electrodes were scanned during a period of 30 s.

SP data were filtered with a low pass filter in the frequency domain in order to avoid edge effects of space domain filters, so that high frequencies were eliminated and low frequencies were preserved (Aubanel and Oldham, 1985). A least-squares analysis method to estimate not only the depth and shape but also to determine the horizontal position of a buried structure from the SP anomaly profile was used (Abdelrahman et al., 2006). The method is based on normalizing the residual SP anomaly using three characteristic points and their corresponding distances on the anomaly profile; then the depth for each horizontal position of the buried structure is determined using the least-squares method. The computed depths are plotted against the assumed horizontal positions on a graph. The solution for the depth and the horizontal position of the buried structure is read at the common intersection

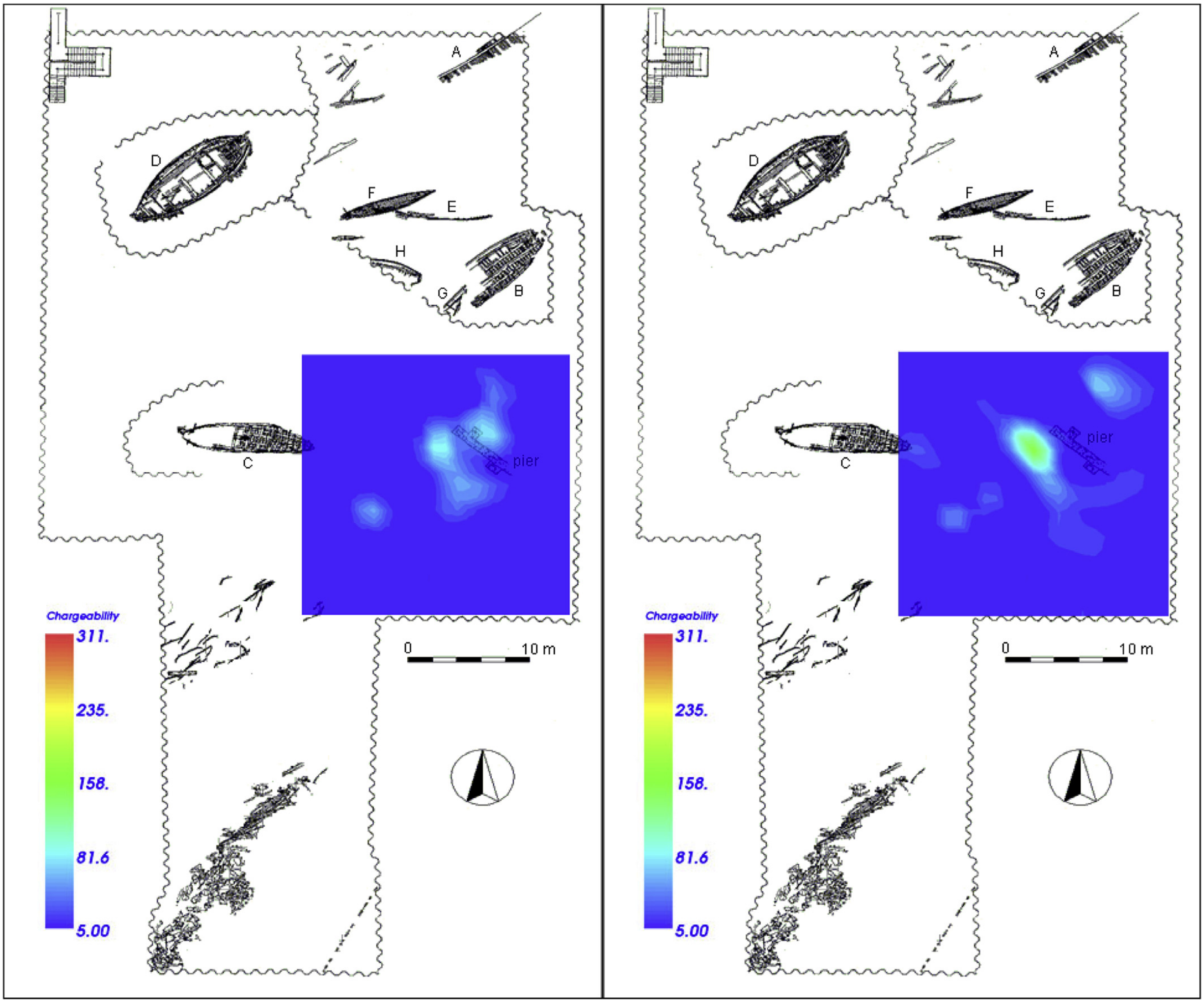

Fig. 7. The layers 2 and 4 (respectively m 1.5 and 2.5 depths) overlaid in transparence on the excavation plan.

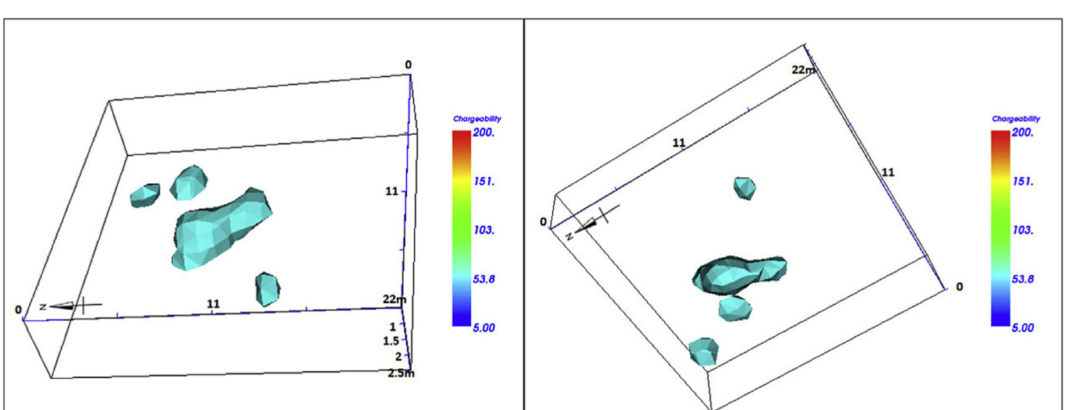

Fig. 8. 3D iso-IP images.

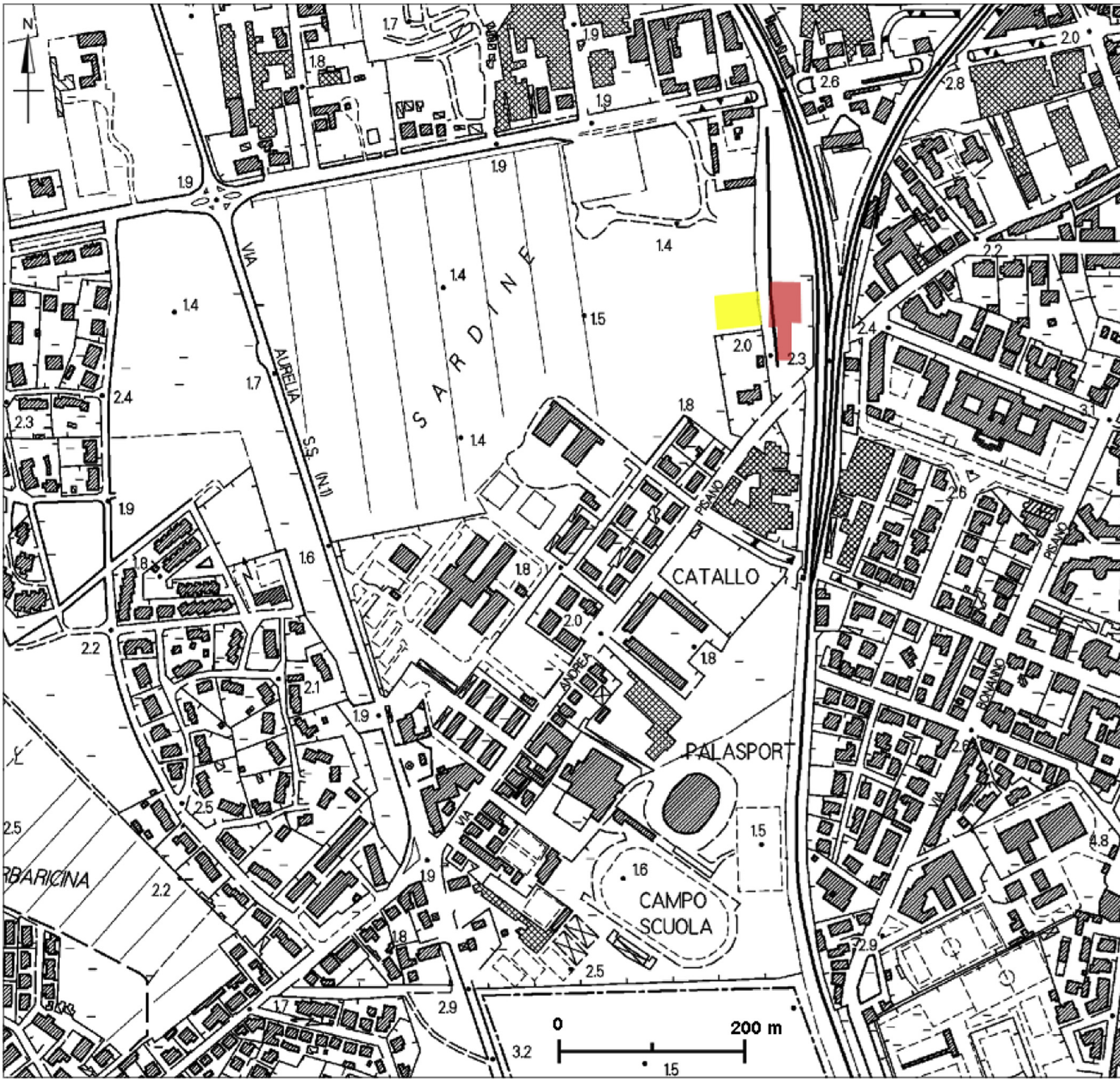

Fig. 9. Location of the Self Potentials surveyed area (in yellow) immediately to the west of the archaeological excavations site (in red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of the curves. Knowing the depth and the horizontal position and applying the least-squares method, the shape factor is determined using a simple linear equation. Procedures are also formulated to estimate the polarization angle and the electric dipole moment. The method is semi-automatic, and it can be applied to short or long residual SP anomaly profiles. These processed data are used to build the Self Potential map shown in Fig 10. Using the aforementioned method, the depth of the SP anomalies was estimated at between 5 and 6 m.

The result of this research shows that the Self Potential values vary between −100 and 300 mV. According to Drahor (2004), the high positive SP anomalies were interpreted as due to a structures (Fig. 10A–B) such as buried stones. In fact, buried stone foundations relatively non-porous body should interrupt the vertical water flow and give rise to a positive SP voltage above it (Drahor, 2004). The high negative SP anomalies were interpreted as due to ships (Fig. 10C–D). In fact, the wood structures could be related to lose material with many cracks and a relatively larger downward movement of water might. This leads to a negative SP on the ground above it. The moderately positive SP values were interpreted as due to a possible palaeo-river bed (Fig. 10E).

4. The contribution of the multitemporal remote sensing data

The so called “ex Scheibler” area has been the subject of several studies using remote sensing images, especially aerial and, to a lesser extent, satellite images. Although it is not easy to date with

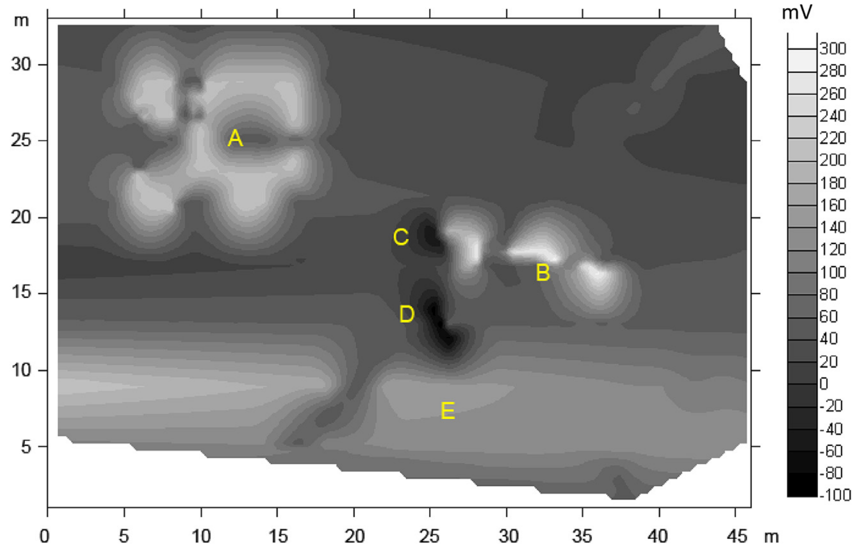

Fig. 10. The Self Potentials map at 5–6 m depth.

discrete approximation the many archaeological and palaeoenvironmental visible traces, they were largely related to *limites* (channels and roads) of the centuriation that can be connected with the deduction of *Colonia Iulia Opsequens Pisana* (Pasquinucci, 1995, 2003a). Centuriation of Pisa is characterized by a pattern of squares of 20 × 20 *actus* (about 710 m × 710 m), oriented NW–SE at an angle of approximately 33°. Some minor irregularities are attributable to adjustments to the ancient topographic surface or to the overlap of ancient agricultural divisions dating back to different periods, repeated over time in areas that have a difficult hydro–geologic equilibrium.

Two excavation campaigns in 1983–1984 have involved a small sector of the NW part of "ex Scheibler" area, starting from crop-marks recognized by M. Cosci in aerial photographs taken by Tuscany Regional Administration in 1980. The excavations have brought to light some Roman ditches and, at a greater depth, archaeological levels relative to an Etruscan settlement of the Archaic period (6th century BC), and material dating back to the Middle Bronze Age (Bonamici, 1987; Bruni, 1999: 121–123). The traces visible in these aerial photos (Bruni and Cosci, 2003) were verified both in the excavation site of San Rossore (Bruni, 2003: 75–78) and in the nearby area (Bruni, 2002, 2003: 25–26: 98).

A recent systematic work of cartographic restitution of traces visible in air-photos of the last 70 years (1943, 1945, 1951, 1953, 1954, 1978, 1980, 1986, 1988, 1996, 1999, 2008, 2009, 2010) georeferenced on the cartography of Tuscany Region (*Carta Tecnica Regionale* – CTR), in a scale of 1:10,000, has allowed to reconstruct many aspects of the ancient topography of the Sardine area, that is in the so-called "ex Scheibler" area (Bini et al., 2012). Analyzed frames have allowed to identify numerous crop-marks, mostly with the same orientation of the centuriation. They can be interpreted as boundaries of land parcels; as aforementioned, previous excavations have documented that some of them correspond to drainage channels. Data from restitution of all traces recorded have defined a detailed picture of the area (Bini et al., 2012: 143–144), more complex than the previous one, which was based only on aerial photos of 1970s and 1980s (Ciampoltrini et al., 2009: 55; Ciampoltrini et al., 2010–2011: 107–108).

Compared to the recent cartographic restitution of traces from photo interpretation (Bini et al., 2012, Figs. 9.3 and 9.11), based mainly on crop-marks visible in vertical aerial photos of Royal Air Force (1943, 1945) and the so-called "*Volo Base*" (1954), and in an oblique air-photo of BLOM-CGR (*Compagnia Generale Ripreseaeree*) taken in 2009, other features can be added with further aerial and satellite images, which confirm and integrate the reconstructed pattern.

The air-photos of Pisa during the Second World War (when the city was heavily bombed) are very interesting. They were taken by RAF between 1943 and 1945, and document a completely different landscape with respect to current one. In particular, they document the "ex Scheibler" area, still completely free from structures (Fig. 11). Among the RAF photos, one taken in June 9th 1944 is very interesting (Fig. 11A), although it does not cover completely the study area. It shows some traces in the southern sector of the area, which was later occupied by buildings.

Among the historical photos, that of the "*Volo Base*", taken August 1st 1954 (strip n° 7, frame n° 2051) is certainly the most interesting. It shows many traces in the southern and south-eastern sectors of the study area (Fig. 12), still perfectly visible before urban expansion that has affected the site. Other subsequent vertical air-photos document the area: i) one probably taken during 1950s or in the early 1960s shows a few traces in the eastern sector (Fig. 13A); ii) another taken by the *Istituto Geografico Militare* (IGM) in July 24th 1965 documents some anomalies due to the different growth of vegetation, in particular in the central sector (Fig. 13B); other two photos, taken by the Tuscany Regional Administration in 1980 (iii) and 1996 (iv) show many crop-marks and document the progressive urbanization of the southern sector (Fig. 13C–D). Many interesting crop-marks are also visible in an oblique air-photo taken in August 25th 2009 by BLOM-CGR (Fig. 14) and in particular in a satellite GeoEye-1 image of July 30th, with a geometric resolution of about 0.5 m (Fig. 15). Other interesting data are also in an oblique air-photo taken in September 15th 2012 by BLOM-CGR (Fig. 16A) and in a GeoEye-1 image of August 11th 2013 (Fig. 16B).

The cartographic restitution of the traces visible in these air-photos and satellite images, previously rectified, allowed to integrate the previous reconstruction of the ancient topography of the "ex Scheibler" area (Fig. 17). Indeed, it is difficult to date and interpret all the traces. Many of them are field boundaries and consist in channels, ditches and probably also in roads and paths. Considering their orientation, most of them could be ascribed to centurial axes, both the main *limites* of *centuriae* (i.e. *kardines* and

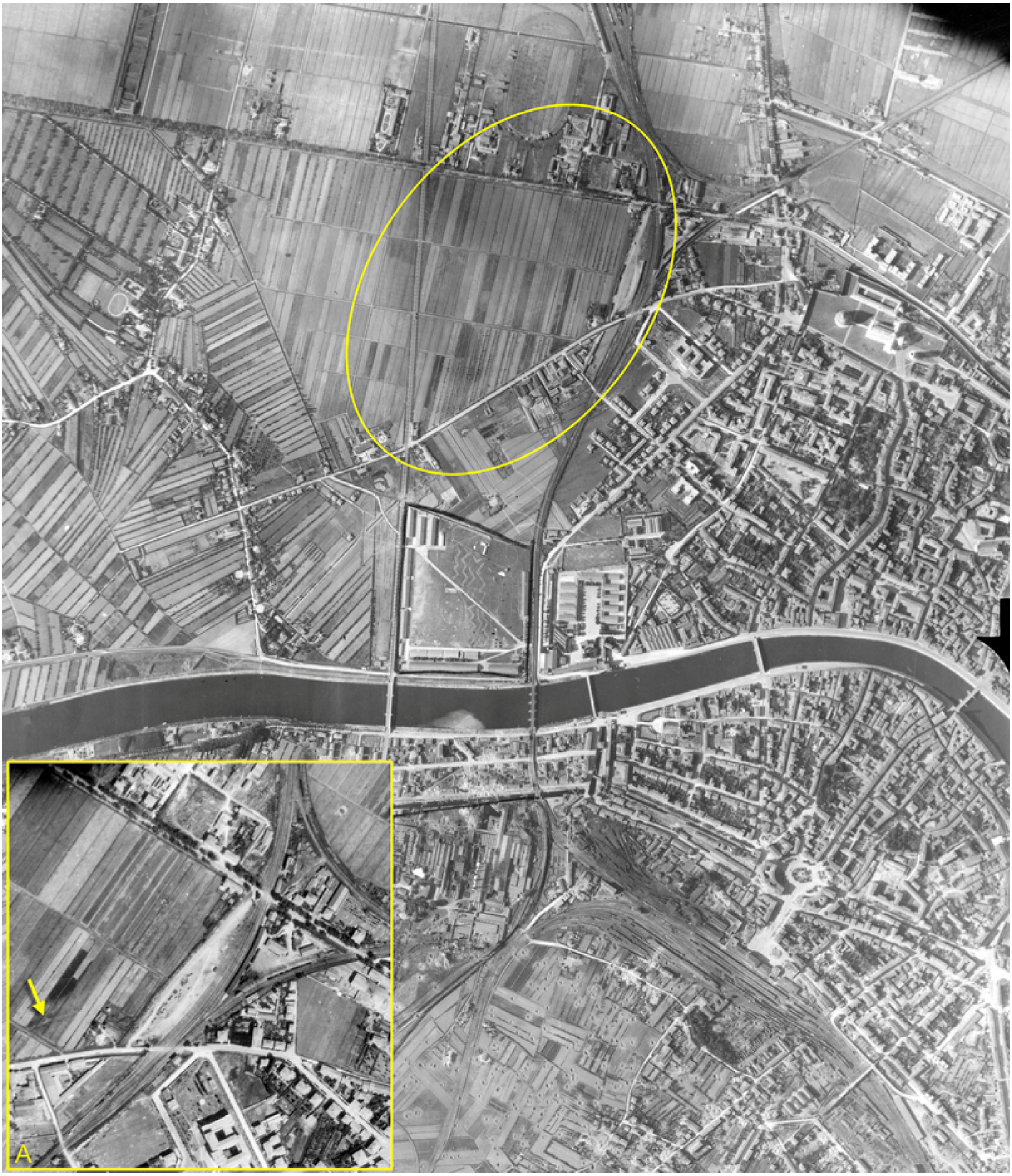

Fig. 11. The study area (yellow oval) in an air-photo of the Royal Air Force taken in September 6th 1943 (strip n° 15, frame n° 3042); it is possible to see the craters of the bombing in the south-western periphery of the city, close to the central station. In the square (A) a detail of a RAF air-photo taken in June 9th 1944 (strip n° 327, frame n° 4015). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

decumani) and internal divisions, arriving at plots of a few dozens of square meters. It is also possible to note traces that ore oblique with respect to the orientation of the land division, probably related to the reclamation or maintenance activities following the definition of the network of *limites*. The main axes are large up to 6 and 9 m, while the secondary ones and the smallest are approximately 3 and 1–2 m large, respectively.

Considering the dates and the periods of acquisition of the images, and due to the land use of the area, cultivated arable, it is possible to see that the summer is the best season for the visibility of the crop-marks. In particular, the images taken between the second half of July and the end of August show the greater number of traces; in some years, also June and the first half of September are good periods of visibility of the archaeological and palaeo-environmental anomalies. This is confirmed, for example, by some satellite images visible in Google Earth and taken from Ikonos-2 in June 13th 2003 and from QuickBird-2 in January 31st 2004, when the terrain was milled, or from QuickBird-2 in April

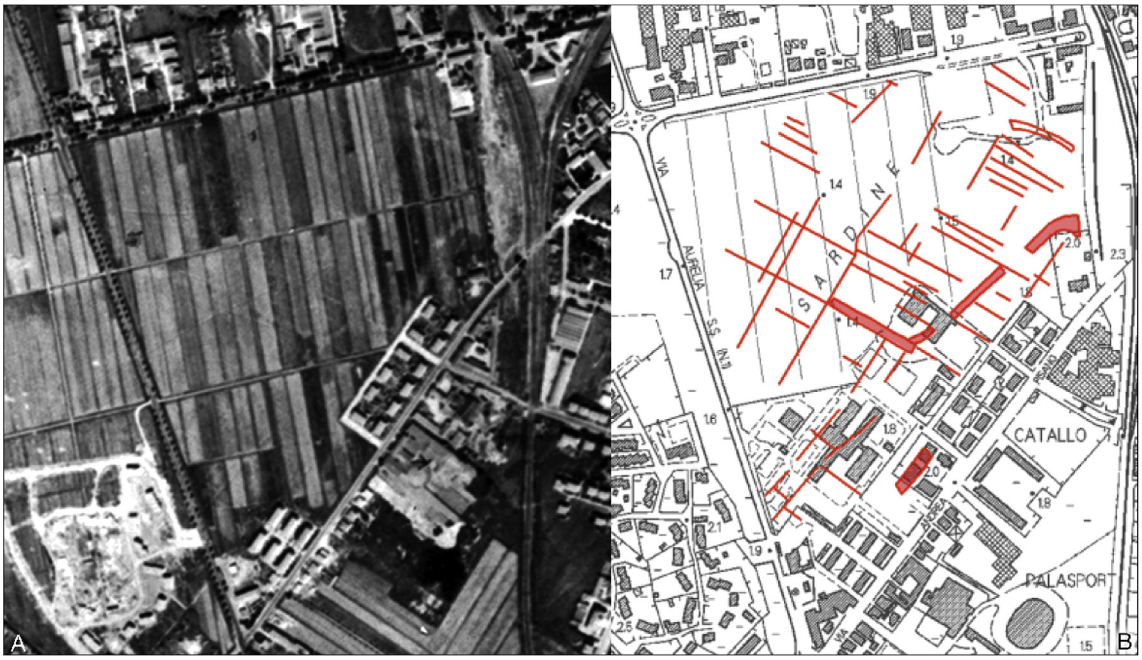

Fig. 12. The “ex Scheibler” area: A, air-photo taken in 1954 (the so called “*Volo Base*”); B, cartographic restitution of the traces (from Bini et al., 2012, Fig. 9.2).

Fig. 13. Four air-photos of the “ex Scheibler” area: A, undated (from Camilli, 2004, Fig. 2); B, IGM of 1965; Tuscany Regional Administration of 1980s (C; from Ciampoltrini et al., 2010–2011, Fig. 1) and 1996 (D; from http://www502.regione.toscana.it/geoscopio/fototeca.html).

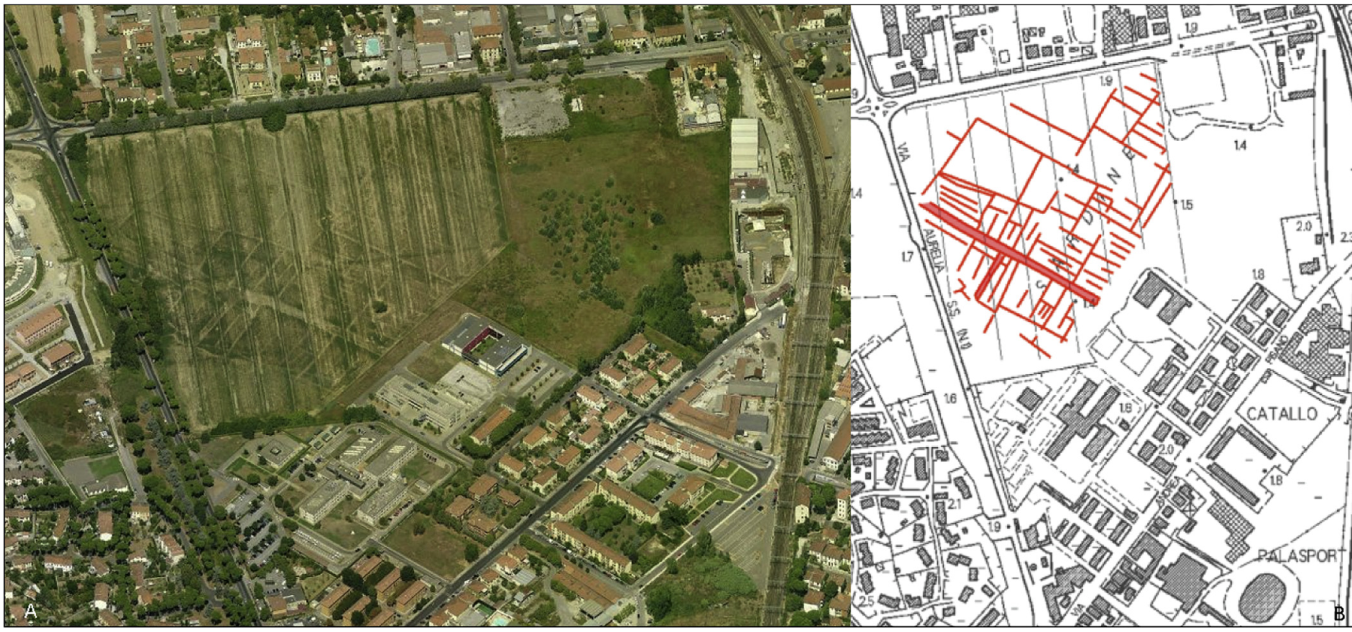

Fig. 14. The "ex Scheibler" area: A, oblique air-photo taken by BLOM-CGR in 2009 (from Bing); B, cartographic restitution of the traces (from Bini et al., 2012, Fig. 9.2).

Fig. 15. The "ex Scheibler" area in a GeoEye-1 image taken in 2012 (from Google Earth).

Fig. 16. The "ex Scheibler" area: A, oblique air-photo taken by BLOM-CGR in 2012 (from Bing); B, GeoEye-1 image taken in 2013 (from Google Earth).

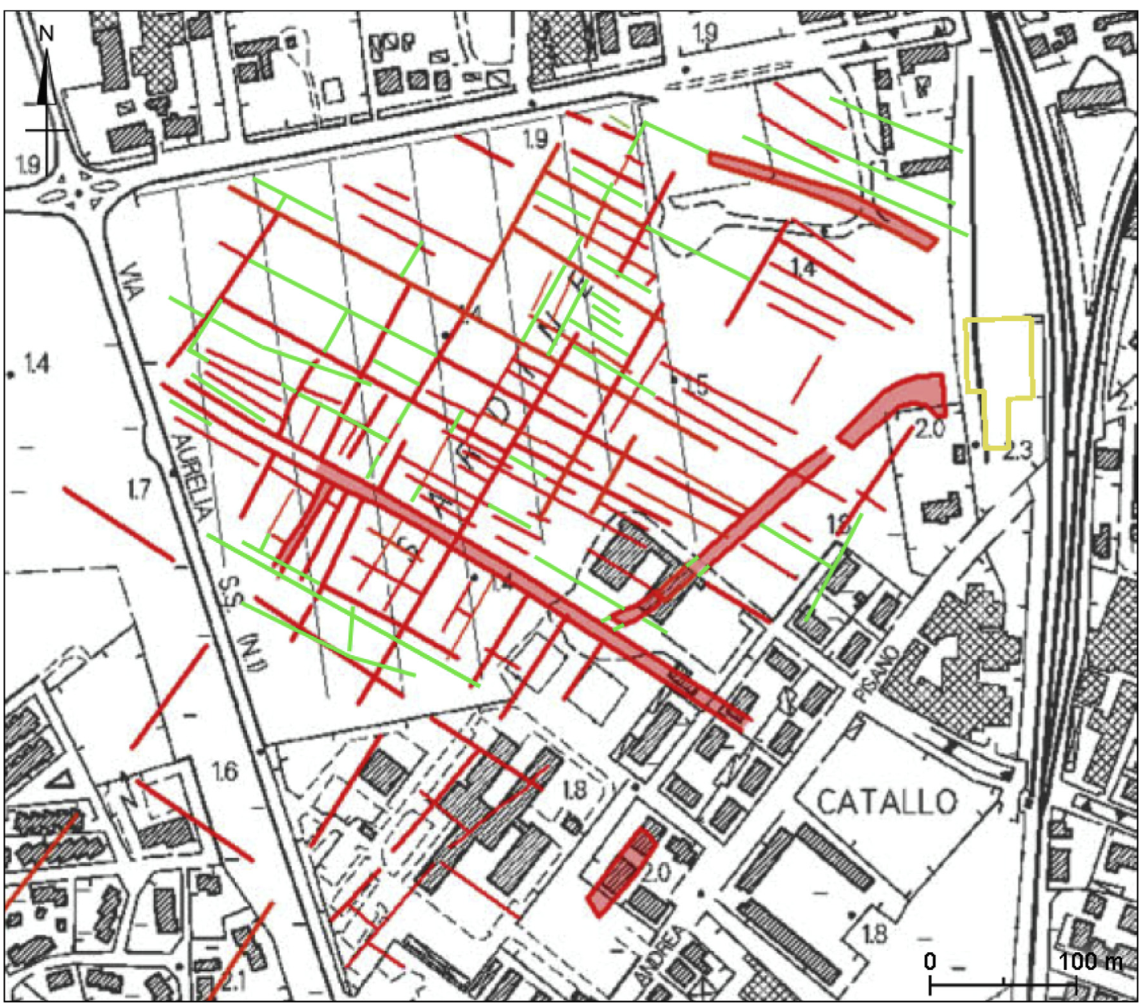

Fig. 17. Cartographic restitution of the traces visible in all air-photos and satellite images: red = data from RAF 1943 and 1945, "*Volo Base*" 1954 and BLOM-CGR 2009 (from Bini et al., 2012, Fig. 9.2); green = data from other images in Figs. 12, 13 and 15; yellow = boundaries of the excavation area of San Rossore. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

27th 2008 and from GeoEye-1 in March 27th 2012, when the terrain was covered by high vegetation (cultivations) or even from GeoEye-1 in July 2nd 2010, when the cultivations were reaped and the ground was covered by stubble without new spontaneous vegetation. Conversely, the images taken during summer document a different situation, more favorable to the visibility of anomalies linked to buried features. After the harvest, the stubble are yellowed and the spontaneous vegetation grows more luxuriant where the terrain is more fertile and where there are no buried structures (dark traces); on the other hand, where the terrain is less fertile and there are buried structures (clear traces), the growth of vegetation is sparser. Many traces are clear in most of the frames and images, but also they can be interpreted as filling of channels and ditches, which normally produce dark traces; indeed, in this case, the crop-marks are due to the leveling of channels and ditches with clay soil, as result of early medieval climate events that led to widespread water-logging of this part of the territory of Pisa (Ciampoltrini et al., 2010–2011: 107–108). Moreover, in some cases (for example in Fig. 16A) several of the same traces are dark.

It is also important to note that the evidence found in aerial photos and satellite images does not completely match with the results of recent palaeohydrographic and geomorphological studies, based on drillings and GPR and geoelectric surveys. Consistent with previous observations and hypotheses (Bruni and Cosci, 2003), a more complicated paleohydrography governed by river avulsion, meander cutoff and channel reoccupation is

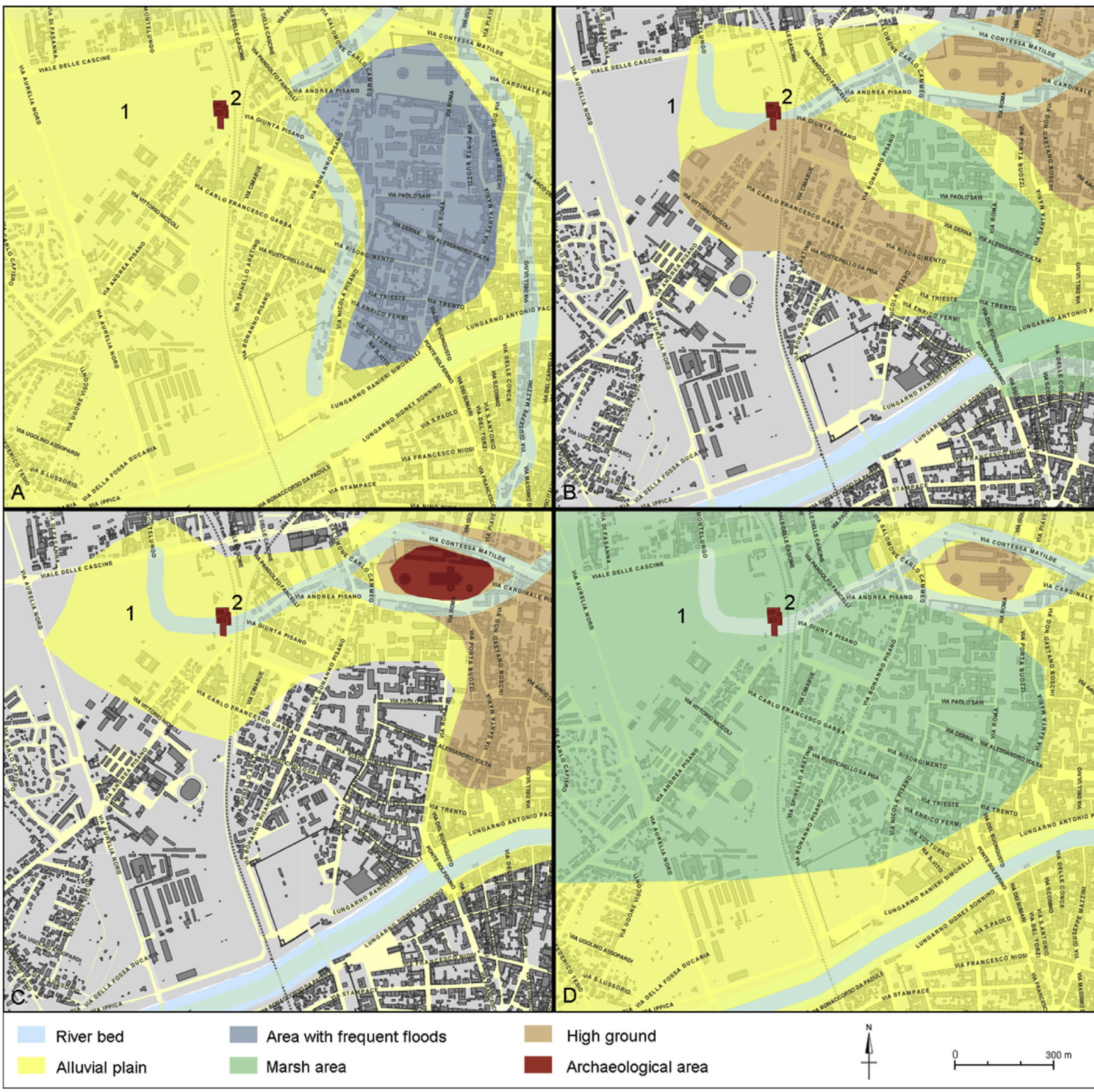

Fig. 18. Paleohydrography of the "ex Scheibler" area during the proto-Historic (A), Etruscan (B), Roman (C) and early Medieval (D) times (maps from http://mappaproject.arch.unipi.it).

reconstructed (Fig. 18). According to these studies (Amorosi et al., 2013; Anichini et al., 2013: 13–27, 163–168 and 182–184; Gattiglia, 2013: 11–79), during proto-historic times an N–S directed branch, showing orientation compatible with a branch of the ancient *Auser* River, merged with the Arno channel meters south of the modern Arno river course, in the *Arsenali* area. The confluence of the palaeo-Serchio into the Arno River fits with the geographic descriptions of the historical sources (Strabo, 5.2.5; Pliny the Elder, *N.H.* 3.5.50; Scolius of Ptolemy, 3.1.4; Rutilio Namaziano, 1.566), as was also identified during the research based on the photo-interpretation (Bruni and Cosci, 2003). This channel linking *Auser* and Arno flowed about 200 m to the east of the study area and the confluence occurred approximately 900 m to the SSE. Its existence is documented for the proto-Historic period; whereas, this hypothesis is not confirmed for the more recent periods. In fact, from the Etruscan period to the late Middle Ages, it was reconstructed a situation with two branches of the *Auser* that lined the northern and southern sides of the Duomo Square, forming a river island; immediately to the west, they joined and continued with a single route to San Rossore. Here, in the “ex Scheibler” area, at the western edge of the suburb, according to these studies, the branch of the *Auser* River would have turned to the north, flanked to the west by gardens and farmlands; but in this site no traces of the rivers course are visible in the aerial and satellite data. From this area, it would continue to the north-west until *Madonna dell'Acqua*, where, with a curve to the west, it flowed into the sea in the *La Sterpaia* area, following a route similar to that of the so-called *Fiume Morto* (Anichini et al., 2013, Figs. 2.3, 2.4, 10.1, 10.3 and 10.7; Gattiglia, 2013, Figs. 2.10 and 2.11). During the Middle Ages, when there was a gradual waterlogging in the area, due to the abandonment of the water defenses related to the centuriation system, as well as to the rise of the sea level, the *Auser* was the subject of massive hydraulic works, which have led to the progressive shift northwards towards the current course of the Serchio (see also Bruni and Cosci, 2003). In particular, in this period, only the branch to the north of Duomo Square is kept, which bends to the NW with a course partly coincident with that of the modern railway line. Then, the Serchio disappeared near the northern medieval city walls, moving further north.

5. Discussion

As pointed out in Section 2, the San Rossore archaeological area was a depression interested from a minor navigable branch of the *Auser* river (Bruni, 2000, 2003; 2006; Camilli and Setari, 2005; Camilli, 2004; Camilli et al., 2006a; Camilli et al., 2006b; see also http://www.cantierenavipisa.it). The alluvial deposits have been caused from overflowing of the near Arno River which, breaking off the banks, flowed from south. As a result, during the centuries, the southern hedge of the minor branch of the *Auser* River moved from south to north. The archaic front line of the river (6th–5th century BC, age to which huts and wooden structures can be ascribed), was reinforced by structures of stone and posts. A second hedge, dating at Hellenistic age, includes the so called “Hellenistic ship” and a mobile footbridge. The later lines of river can be dated back to Julian-Claudian and Flavian ages, late to the 2nd century AD, the 3rd – 5th century AD and, at last, to the beginning of the 7th century AD: in fact, in these periods, several alluvial events occurred, which have provoked the sinking of numerous ships and of their cargos. Although some structures for arrangement of the river shore and others structures (probably for docking) were found, there is no evidence that can be referred to a port context in the strict sense. In fact, the proximity to the city, the insertion in the *centuriatio* system (as highlighted from the photo-interpretation), the absence of evident infrastructures do not allow such

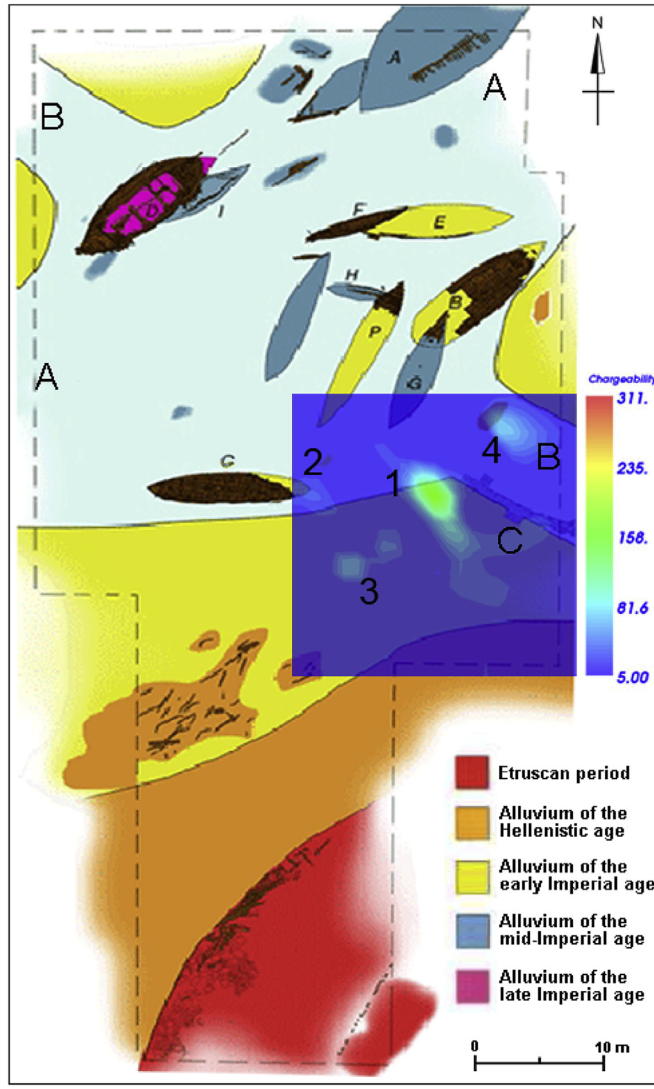

Fig. 19. Depth slice (depth 2.5 m) georeferenced in transparence on the plan of the archaeological site of San Rossore, where the chronological phases are distinguished by colors and the palaeochannels are in azure (from Camilli et al., 2006a, 2006b; with few additions): 1–4 anomalies that probably reflect the presence of ships or sections of them or shiploads; A, branch of the *Auser* River; B, palaeochannel; C, dockage. The layers which enclosed boats, divided on the basis of geological and archaeological stratigraphy, were generated by the flooding of the Arno River between the 2nd century BC and 7th century AD; so they were due to alluvial deposits from the south, which have climbed the bank of the branch of the *Auser* River making advance the south bank.

statement. In the Roman age, it is most probably a stream near the town and subject to heavy river traffic, which cross a rural area and with some private docking for the farms and the nearest *villae* (Camilli, 2004: 59–60).

The area inside the archaeological site that was surveyed using geophysical prospecting (12 m × 12 m) is between the ship C (south-west), a possible dock (south-east) and the excavated parts of the boats G and P, to the north (Fig. 19). The context is affected by the Augustan-Tiberian alluvium, which involved many boats, and by the mid-Imperial alluvium. The ship C was a big fast fluvial ship, 4 m long, whose structure is preserved in excellent condition. It has been involved in the Augustan-Tiberian alluvium. The boat G was a barge with flat bottom and found prow, ascribable to the mid-Imperial alluvium. Only the prow has been dug, but the total length (approximately 9 m) was identified. The boat P has been

probably involved in the Augustan-Tiberian alluvium; and also this boat has been only identified and partially dug. The rests of the hull belong to a flat bottom boat, probably similar to the nearby boat G. Immediately to the south-east of the investigated area, there is the only structure that has been recovered (until now) in this landing place and it was a dockage (Fig. 19C): it is a kind of wharf realized in rock and sand mortar, with two foreparts, lying along the western hedge of one of the secondary artificial channel (Fig. 19B), with NW–SE direction and that crossed the branch of the *Auser*, which flowed from NE to SW (Fig. 19A). The structure, approximately 8 m long and with a width of 1.60–1.70 m, probably dates back to the Tiberian-Claudian Age and it could be the landing place of a private *villa* of the suburb (Camilli, 2004: 68).

The geophysical surveys have shown the presence of features at a depth of approximately 2–2.5 m, at a high level in comparison with that achieved by the excavation, whose depth ranges from 5.5 to 9 m below ground level (see above Section 3.2). A central and large anomaly (Fig. 19, n° 1) could be interpreted as a ship (the same of Carrozzo et al., 2003, Fig. 9; B) located immediately to the west of the already known pier discovered by the archaeological excavation; moreover, another anomaly in the north-western side of the surveyed area (Fig. 19, n° 2) could be related to the eastern edge of the ship C; while it is difficult to interpreter other two small anomalies (Fig. 19, n° 3 and 4).

The SP survey concerns also an area of about 35 m × 45 m inside the area of 10,000 sqm (protected by law) located immediately to the west of the excavation site, in the “ex Scheibler” area, where aerial photos show an intricate network of traces, mostly corresponding to *limites* of the Roman *centuriatio* and that the excavations have demonstrated to be drainage channels (Bini et al., 2012: 143–144; Anichini et al., 2013: 182–184). As aforementioned (Sections 2 and 4), the centuriation of Pisa was defined in the Triumvir or Augustan Age, between 42 and 27 BC, as a result of the deduction of the *Colonia Iulia Opsequens Pisa*. It has been interested the vast territory bordered to the west from the large bay extending from the headland of *Gronda dei Lupi* in the south, near the Leghorn, to lake Massaciuccoli in the north, where the branches of the delta of the Arno River and those of *Auser* flowed (Pasquinucci, 1995, 2003a). The survivals and traces of the Roman *centuriatio* of Pisa are best preserved and identifiable by photo-interpretation especially in the territory north, NE and east of the city (Cosci and Brown, 2003; Bini et al., 2012), in the most stable areas from the hydrogeological point of view. Therefore, the concentration of visible traces in the “ex Scheibler” area is almost an exception in the territory NW of the city.

The SP survey have highlighted, at a depth of approximately 5–6 m, the presence of some interesting features, which are difficult to interpret (see above Section 3.3). The high mV values seem to document a structure very similar to the pier brought to light in the excavation site (Fig. 20H); the possible remains of the plating of two boats are nearby (Fig. 20I–L). Other structures of uncertain interpretation (the plain in Fig. 20, M–N is hypothetical) can be recognized in the north-western sector. Instead, the interpretation of the large anomaly (high mV values) visible in the southern part of the surveyed area (Fig. 20F) is more difficult. This difficulty is connected to the identification of the nature of some of the traces derived from the analysis of aerial and satellite images. Among these traces, there are two large crop-marks which are very evident and for which the interpretation is not straightforward. In particular, it is unclear whether these are channels or roads. The first anomaly (Fig. 20B), approximately 6 m (= 20 feet) wide, oriented NE–SW, is to be interpreted as a *kardo*, coinciding with the network of the land division. The other one (Fig. 20A), which is approximately 9 m (= 30 feet) large and orthogonal to the previous one, is more problematic: it may be interpreted as a road, and more precisely as a *decumanus*; nevertheless, it appears shifted of approximately 100 m compared to the theoretical centuriation grid (Fig. 20C; Fig. 21). In addition to this, the archaeological excavation, located in the intersection of the two axes mentioned above, showed only the presence of drainage channels (Bini et al., 2012: 143–144). These difficulties of interpretation are also related to the characteristics of the crop-marks and to their aspect in the air-photos and satellite images, as clear (more frequently) or dark (more rarely) traces (see above Section 4). In this regard, it is important to highlight that in some images the two features labeled A and B in Fig. 20 seem roads flanked by ditches. The same remarks regard the feature labeled D, more evident in some air-photos (Figs. 12 and 13C), which has an orientation SW–NE divergent from that of the centurial axes. The north-eastern edge of this feature was investigated by SP measurements, which have highlighted a high mV anomaly (Fig. 20F) consistent with two possible interpretations: filled channel or road flanked by two ditches. In the

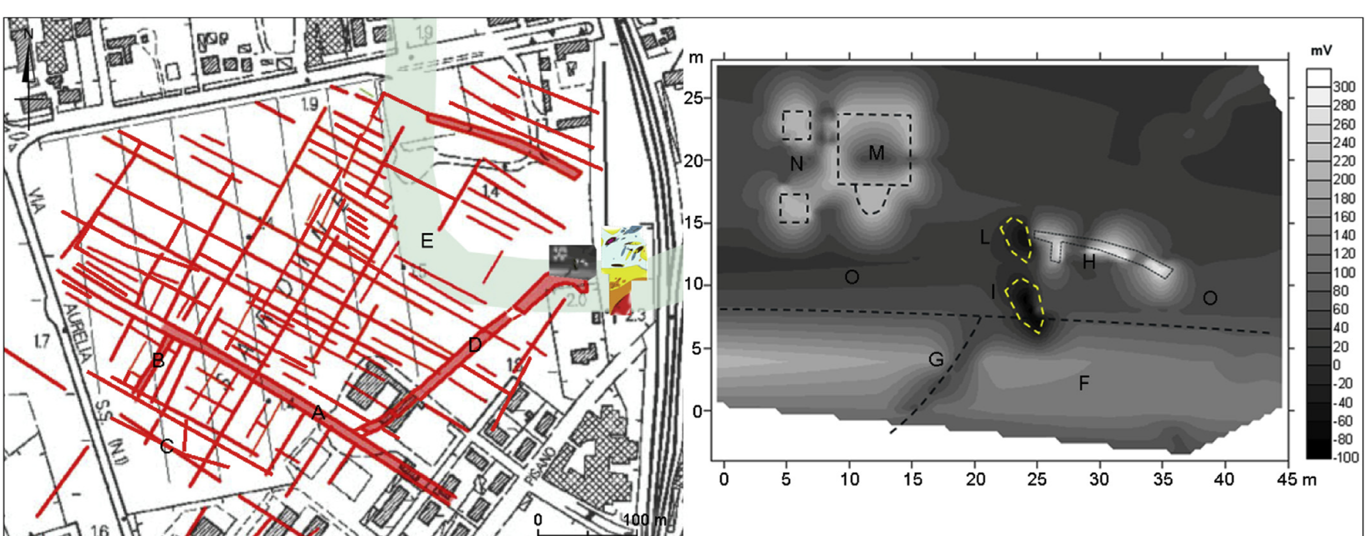

Fig. 20. Depth slice (depth 5–6 m) georeferenced on the cartographic restitution of Fig. 17 and enlarged to the right; in azure the paleohydrography (data from http://mappaproject.arch.unipi.it). The plan of the archaeological site of San Rossore in Fig. 18 is also georeferenced.

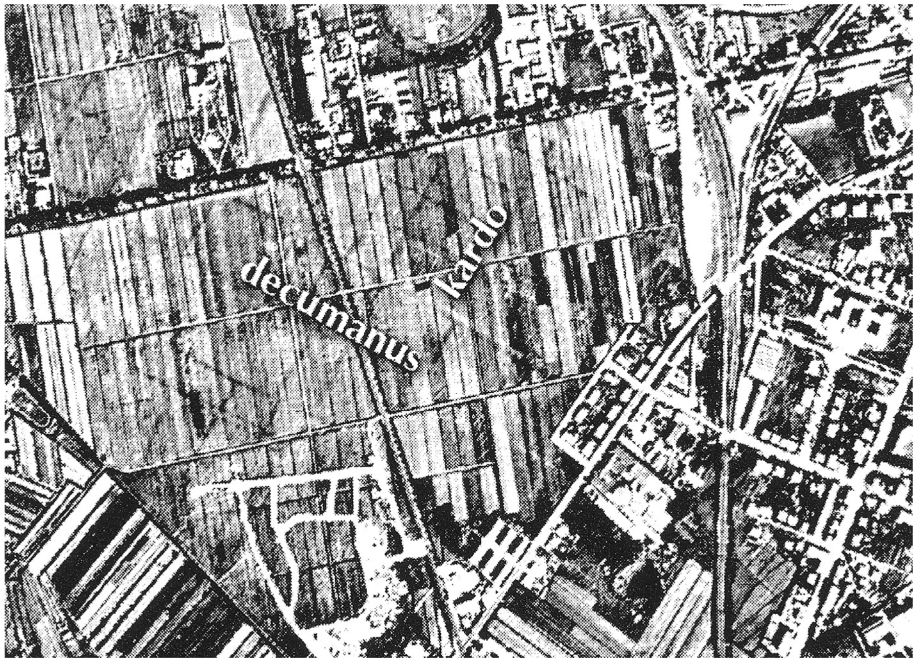

Fig. 21. Aerial photo taken in 1970s by the Tuscany Regional Administration (from Ciampoltrini et al., 2010–2011, Fig. 2): the image allowed the identification of a section of the centuriation of Pisa, with a *kardo* oriented NE–SW and a *decumanus* oriented NW–SE. The main traces, that can be ascribed to roads and channels, are restituted in Fig. 17.

second hypothesis, the northern hedge of the road could be flanked by a channel (anomaly labeled O in Fig. 20), in which the possible boats L and I could be located; the possible pier H probably could extend along its northern side. Moreover, also the narrow anomaly labeled G in Fig. 20 could be interpreted as a ditch, which crossed the anomaly F.

However, it is possible to make two additional remarks that complicate the reconstruction of the ancient topography of the area. In fact, it is important to remember (see above Sections 2 and 4) that in the archaeological site of San Rossore was excavated the intersection of a centurial channel oriented NW–SE (Fig. 19B) and a branch of *Auser* River oriented NE–SW (Fig. 19A), which has progressively moved toward the north. Now, the feature labeled D in the air-photos interpretation and F in the ERT time slice (Fig. 20) is exactly in the extension in SW direction of the branch of *Auser*. Moreover, as mention in Section 4, according to the studies on the geomorphology and paleohydrography of the area, the reconstruction of the route of the *Auser* is quite sure until a few hundred meters east of the excavation site of San Rossore, while the palaeohydrographic network in the "ex Scheibler" area is still uncertain (Anichini et al., 2013: 177–178 and 182–184). The branch of the *Auser*, coming from east, would have turned to the north. Now, the feature labeled F in the SP depth slice (Fig. 20) is exactly in the extension in W direction of this watercourse, after its crossing of the excavation area. Furthermore, even though no traces of this palaeo-river bed are visible in the aerial and satellite images, its georeferentiation in the cartographic restitution of the crop-marks shows that this hypothetic branch of the *Auser* corresponds to an area characterized by few anomalies of the remote sensing data regarding boundaries of gardens and farmlands, which could flank the river.

6. Conclusions

Geophysical prospecting and integrated analyses of multitemporal aerial and satellite documentation revealed charac teristics that could be interpreted as archaeological features in the San Rossore excavation site and in the nearby "ex Scheibler" area. The new acquired data allow to enhance the interpretation of this portion of the ancient plain at the north-western periphery of Pisa. In particular, inside the excavation area a possible new ship was identified, while in the nearby territory was highlighted the presence of channels and roads (most of them referable to the Roman centuriation), structures (among which also a possible pier) and two other possible ships along a palaeochannel. These data allow to contextualize the most important archaeological site of San Rossore in the ancient landscape between Pisa and the Tyrrhenian coast.

With regards to geophysical prospecting, it is important to emphasize the good results of the two applied methods (SP and IP measurements), which have a good performance in the typical geological conditions of the site and considering the characteristics of the archaeological evidence. In particular, inside the excavation area, the research has demonstrated that in the case of buried remains which are insensitive to the resistivity changes the IP measurements can be a useful method. In fact, the IP values allow to reconstruct the exact spatial position and size of a possible buried ship.

Moreover, it is important to highlight the importance of the acquisition of multitemporal remote sensing data, both aerial and satellite, for the reconstruction of the ancient landscape. Finally, the test site outside the excavated area suggest that when the photo interpretation is not enough to unambiguously identify some features, it is advisable to use electric methods to verify and establish the difference between channels or roads, which still remains one of the biggest problem in the study area; therefore, the application of this type of geophysical prospecting could be extended for the reconstruction of the history of the San Rossore area, also in a diachronic perspective.

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